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GALILEO MISSION PLANNING FOR LOW GAIN ANTENNA BASED OPERATIONS

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ABSTRACT

The Galileo mission operations concept is undergoing substantial redesign, necessitated by the deployment failure of the High Gain Antenna, while the spacecraft is on its way to Jupiter. The new design applies state-of-the-art technology and processes to increase the telemetry rate available through the Low Gain Antenna and to increase the information density of the telemetry. This paper describes the mission planning process being developed as part of this redesign. Principal topics include a brief description of the new mission concept and anticipated science return (these have been covered more extensively in earlier papers), identification of key drivers on the mission planning process, a description of the process and its implementation schedule, a discussion of the application of automated mission planning tools to the process, and a status report on mission planning work to date.

Galileo enhancements include extensive reprogramming of on-board computers and substantial hardware and software upgrades for the Deep Space Network (DSN). The principal mode of operation will be onboard recording of science data followed by extended playback periods. A variety of techniques will be used to compress and edit the data both before recording and during playback. A highly-compressed real-time science data stream will also be important. The telemetry rate will be increased using advanced coding techniques and advanced receivers.

Galileo mission planning for orbital operations now involves partitioning of several scarce resources. Particularly difficult are division of the telemetry among the many users (eleven instruments, radio science, engineering monitoring, and navigation) and allocation of space on the tape recorder at each of the ten satellite encounters. The planning process is complicated by uncertainty in forecast performance of the DSN modifications and the non-deterministic nature of the new data compression schemes. Key mission planning steps include quantifying resources or capabilities to be allocated, prioritizing science observations and estimating resource needs for each, working inter-and intra-orbit trades of these resources among the Project elements, and planning real-time science activity. The first major mission planning activity, a high level, orbit-by-orbit allocation of resources among science objectives, has already been completed; and results are illustrated in the paper.

To make efficient use of limited resources, Galileo mission planning will rely on automated mission planning tools capable of dealing with interactions among time-varying downlink capability, real-time science and engineering data transmission, and playback of recorded data. A new generic mission planning tool is being adapted for this purpose.

1. MISSION OVERVIEW

Galileo is on its way to Jupiter to study the giant planet's atmosphere, satellites and magnetosphere with the most capable suite of instruments ever placed on a planetary spacecraft. Galileo is actually two spacecraft currently traveling attached. The Probe will separate in July 1995 and enter the Jupiter atmosphere on December 7, 1995. For about 75 minutes during Probe descent, data from its seven instruments will be relayed to the Orbiter for subsequent transmission to Earth. The Orbiter will then conduct a 23-month-long tour of the Jupiter system including ten close encounters (200-2700 km altitude) with the Galilean satellites while returning data from its eleven instruments. Details of Galileo's science objectives and the instruments sent to accomplish them are provided in Reference 1.

A high level timeline of the mission is shown in Figure 1. Galileo was launched on a Venus-Earth-Earth-Gravity Assist (VEEGA) trajectory in October 1989. This trajectory has provided opportunities to return science data from the first two asteroid encounters (asteroids Gaspra and Ida) as well as data from close flybys of Venus and Earth (twice). Galileo's images of Ida provided an unexpected

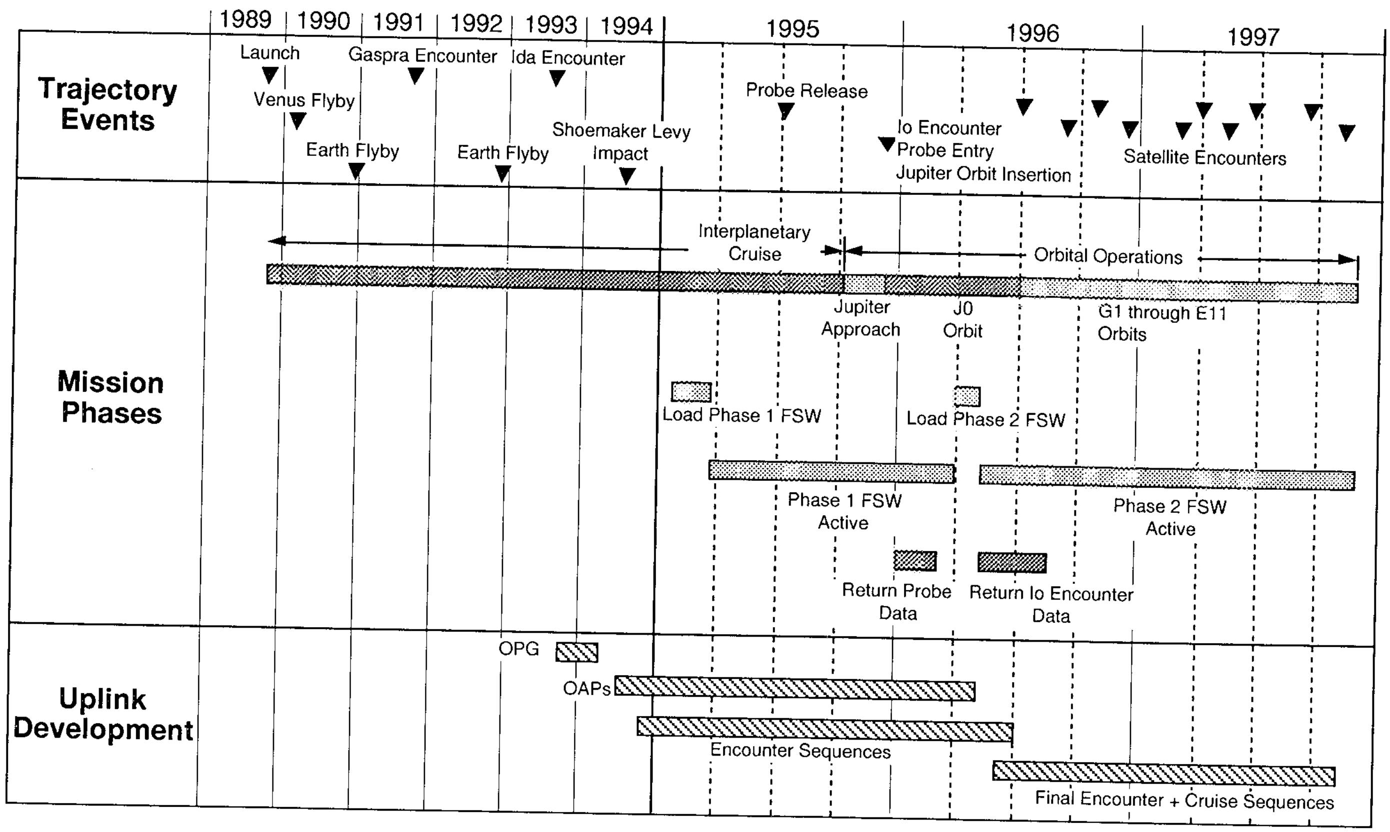

Figure 1. Mission Overview

bonus, discovery of a small moon orbiting the asteroid. Shortly after submission of this paper, Galileo will observe a remarkable target-of-opportunity, the impact of comet Shoemaker-Levy 9 into Jupiter.

The Galileo design incorporated a High Gain Antenna (HGA) capable of downlinking an 800x800 pixel image in one minute. At launch, the HGA was folded umbrella-fashion to fit in the Space Shuttle bay; and, for thermal reasons, deployment was not scheduled to occur until about 1.5 years after launch. The deployment sequence resulted in a partially open antenna, and a wide range of corrective actions has been unsuccessful (see Reference 2). In late 1991 a new mission concept using the Low Gain Antenna (LGA) was devised to capture most of the original science objectives if the HGA could not be opened. The new concept is summarized here, details can be found in Reference 2.

In cooperation with the Deep Space Network (DSN), systems are being developed that will provide two orders of magnitude improvement in the downlink of science information from Galileo to Earth. Half of this improvement will be in actual data rate improvements resulting from application of advanced error-correcting coding techniques and advanced technology receivers that enable shifting all of the power of the radio signal into the telemetry side-bands and also facilitate arraying of multiple tracking stations. The other order of magnitude improvement will be achieved by increasing the information density of the downlink via reprogramming of onboard computers to apply state-of-the-art data compression techniques (References 3 and 4) as well as extensive onboard editing of data from the science instruments.

The Galileo science community estimates that 70% of the original science objectives can be achieved by the new mission concept. This includes all of the objectives associated with the Probe, since the data quantity is small and the full data set can be recorded on the Orbiter and returned using the LGA even without the spacecraft software and DSN enhancements.

Figure 2 illustrates the new operational concept for a typical orbit. Since most of the key opportunities for imaging and other remote sensing occur in a 7-day "encounter" period centered (roughly) at perijove,

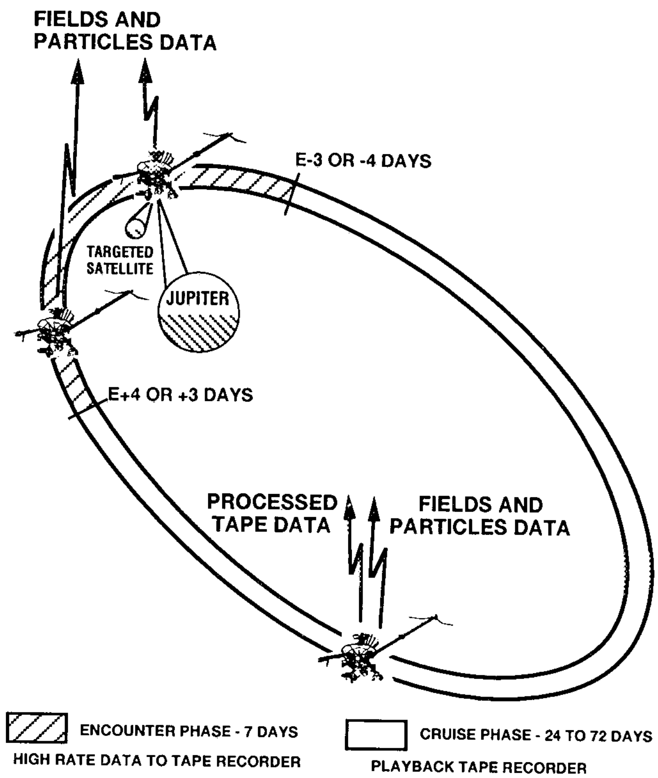

Figure 2. Typical Orbit

these observations can be recorded and subsequently played back in compressed or edited form during the "cruise" period between encounters (24-72 days). In addition to the return of recorded encounter data, a continuous stream of highly-edited real-time data (predominently from the fields-and-particles instruments) can be downlinked throughout both the encounter and cruise periods.

The flight software (FSW) modifications that provide these new capabilities (designated "Phase 2" in Figure 1) are currently being developed and will be uplinked in the spring of 1996. The Phase 1 FSW modifications will be uplinked early in 1995 and will provide for protection of the Probe data against tape recorder problems by storing key data in the on board computer.

2. DRIVERS ON MISSION PLANNING

With a mission design that includes six years of interplanetary cruise and two years of orbital operations, the subject of what mission planning to do when has long been debated within the Project. The need for early development and testing of the highly critical sequences for Probe data relay through the Orbiter and the Jupiter Orbit Insertion maneuver was never at issue, but there has been less certainty about the level of detail of planning for orbital operations. For the original mission concept there was concern about the difficulty of building and implementing eleven complex satellite flyby sequences (an Io flyby on the day of Jupiter orbit insertion plus ten orbital encounters), with substantial contention among the eleven orbiter instruments for observation time and sequence memory (particularly the four instruments on the scan platform). So the pre-launch Project Plan called for early development of detailed plans that would precisely allocate these resources.

The modifications for LGA-based operations added to the list of critical resources while making precise early allocation of these resources a lot more difficult. The most significant resource for LGA-based operations is the downlink capability (usually referred to on the Project as "BTG" or "bits-to-ground", although commonly measured in megabits). Space on the tape recorder ("bits-to-tape") is also a crucial commodity, since the recorder can only be filled once for each satellite flyby and for the "best" orbits (long periods between flybys coupled with small Earth-Jupiter range) there is enough BTG capability to empty the tape recorder at acceptable compression ratios. The criticality of the tape recorder to the LGA-operations concept has also added the cycle-life of the recorder to the list of resources that must be closely managed.

The interplanetary cruise phase encounters have provided experience in dealing with these scarce resources and have generally confirmed the need for detailed early planning. The Venus and Gaspra flybys were constrained largely by space on the tape, since there was ample playback capacity at subsequent Earth flybys; the Earth flybys themselves were useful exercises in dividing up observing time; and the Ida flyby was the first experience with severe BTG limitations. These experiences left no one doubting the wisdom of having detailed plans in place well in advance of the high activity periods.

The Galileo mission planners must, however, now deal with a high degree of uncertainty in allocating BTG (their most critical resource). The DSN enhancements discussed in Section 1 include the first application of new technology in several areas, and, while confidence is high, no comprehensive end-to-end performance test will be possible until shortly after the Phase 2 FSW modifications are loaded in the Spring of 1996. Uncertainty in performance of data compression algorithms is also a major hindrance to precise planning. Compressibility of some imaging data (and the corresponding BTG allocation) will be known to within only a factor of two a priori.

Another driver on the planning process is the continuing pressure on operations budgets of NASA missions. The mission plan must be structured so that it can be implemented with a staffing level substantially reduced from the original Project Plan.

3. THE MISSION PLANNING PROCESS

Galileo mission planning and sequence development have always used a top-down design process. The products are as follows: (1) the Orbit Planning Guide (OPG) providing a high level orbit-by-orbit allocation of resources across the tour, (2) Orbit Activity Plans (OAPs), one for each orbit, which suballocate resources among individual activities in a time ordered listing, (3) a set of Orbit Profiles for each orbit, in which the OAP activities are expanded in terms of sequence components which can be automatically converted to (4) an uplinkable command file of 1000-3000 commands. Steps (1) and (2) are viewed as mission planning and are the focus of this paper.

In 23 months the Galileo Orbiter will navigate through an eleven-orbit tour. Experience during interplanetary cruise has shown that the complete sequence planning process for each orbit will take considerably more than two months. Hence the sequence planning process must begin before the Jupiter tour begins. This has led to a schedule (see Figure 1) under which the OPG was completed in February 1994 and orbit-by-orbit sequence development began in July 1994. In the pre-arrival planning, the encounter sequence for each targeted fly-by of a Galilean satellite will be developed in full detail immediately following the OAP development. All OAPs and encounter sequences are scheduled for completion prior to the first satellite encounter of the tour (July 1996).

The Galileo mission planning process is intertwined with the structure of the Galileo science community. The Galileo flight team at JPL is organized to interface with and support the science investigator teams which are organized by instrument. Each of the instrument and radio science experiments on the Probe and on the Orbiter, is lead by a Principal Investigator (or Team Leader for SSI and Radio Science) with a group of Co-Investigators (or team members). Most of the Galileo investigators are located at other institutions than JPL. The Principal Investigators, Team Leaders, and a number of Interdisciplinary Scientists comprise the Project's senior science planning agency, the Project Science Group (PSG). The PSG has subcommittees - called working groups - which cross-cut the instrument teams to deal with top level priorities and plans in the three major discipline areas called out in the Project Plan: Atmospheres, Satellites and Magnetosphere. All of the Orbiter investigator teams are represented at JPL by an operations support team lead by a Science Coordinator. Through periodic meetings and on-going dialogue of the PSG and the working groups, the mission goals are turned into operations plans at JPL.

As part of the planning process, resources are allocated as early as possible during development. Tape usage (bits-to-tape), telemetry usage (bits-to-ground), and propellant usage (kilograms) were allocated to the discipline working groups as part of the OPG. Within the discipline working groups and as part of the Orbit Activity Plans, those resources get sub-allocated to the eleven instruments and radio science. Tape recorder cycles and sequence memory usage cannot be allocated until a high level sequence is available; they are first allocated in the OAP. As part of sequence adaptation during orbital operations, all of these resources are subject to some re-allocation.

In addition to distributing the key spacecraft resources among the three science disciplines, the OPG also describes the high-level plan for how each science discipline will accomplish its science objectives consistent with the distribution of resources. The process of developing the resource allocations was influenced by a number of factors: experience with the previous (pre-launch) OPG, experience with Galileo planetary encounters on the way to Jupiter, scoping exercises and of course, schedule. Allocations of resources across science discipline areas, based on scientific consideration, are always difficult to get agreement on; the investigators, science elements of the JPL team and the Project Scientist worked together to arrive at the current position. An initial allocation of resources to the working groups over the whole tour was developed by the Project

Scientist. This initial allocation provided the basis for further negotiation and trading of resources between the working groups with the outcome being orbit-by-orbit allocations, driven by and consistent with the characteristics of the orbital tour.

The first two weeks of the 8-week OAP development cycle involve two parallel tasks: building an engineering and navigation "skeleton" plan and initiating work on satellite encounter remote sensing designs for the critical period around closest approach. The skeleton schedules and allocates resources for spacecraft systems maintenance and calibration, attitude updates, optical navigation imaging, radiometeric navigation, and orbit trim maneuvers. The remote sensing design uses sophisticated 3-D cartographic tools to account for target ephemeris, spacecraft trajectory, and scan platform dynamics in laying out mosaic patterns and target-to-target scan platform slews. This must be done at a fine level of detail at the beginning of the OAP to get a handle on the resource needs of the observations near closest approach.

Next, OAP development enters a 4-week iterative period in which the remainder of the science observations are designed, resource needs are estimated, the activity timeline is built, deviations from operating constraints are identified, and all of this is iterated where conflicts are found. During this period the working groups divide BTG and other resources among the participating instruments and the instruments divide them among individual observations. This includes separate BTG allocations for tape recorder playback and real-time science. Conflicts with the "skeleton" are also subject to iteration.

The final two weeks of the OAP cycle are devoted to a last round of constraint checking, review of the integrated product by all participants, and approval by project management.

4. ORBIT PLANNING GUIDE RESULTS

This section summarizes the results of the OPG development completed in February 1994 (Reference 5). In particular, Table 1 summarizes the results of the OPG negotiations among the working groups for allocating BTG and tape recorder space for the orbital tour. The table gives the total BTG available to science during the cruise phase for each orbit (in megabits), the percentage of the BTG allocated to each working group, and the percent allocation of the encounter tape load. The working group allocations for the Io encounter (J0) and the G1 orbit were combined because the expectation is that all of the J0 data cannot be returned prior to the G1 encounter. Some J0 data will be carried over and played back during the G1 cruise period. For the C9 orbit, the total telemetry capability has not been fully allocated to the working groups at the OPG level since it is more than enough to play back the tape. Some additional recording and play back during the cruise period of the orbit is planned.

A number of science trades were necessary to develop the allocations in Table 1. The long-range,

Table 1. OPG Resource Allocation

Orbit	Capability (MBTG)	Satellites		Magnetosphere		Atmosphere	
		% of BTG	% of Tape Load	% of BTG	% of Tape Load	% of BTG	% of Tape Load
J0	170		50%		13%		13%
G1	225	35%	35%	48%	5%	17%	38%
G2	155	22%	58%	70%	18%	8%	25%
C3	110	49%	53%	20%	3%	31%	45%
E4	100	50%	50%	17%	3%	33%	48%
E6	110	40%	53%	40%	8%	20%	40%
G7	90	40%	55%	40%	8%	20%	38%
G8	195	35%	45%	40%	10%	25%	45%
C9	460	24%	53%	40%	16%	14%	50%
C10	200	28%	40%	40%	10%	32%	50%
E11	115	40%	40%	30%	10%	30%	50%
Totals	1930	33%	46%	41%	8%	21%	41%

short-duration orbits of C3, E4, E6, and G7 posed particular difficulty. For the satellite working group (SWG), these orbits contain the high priority target Europa. In the case of the magnetospheric working group (MWG) continuous real-time monitoring of Jupiter's dynamic magnetosphere is their highest science objective. The atmospheric working group (AWG) is more flexible with respect to acquiring specific science objectives during these orbits, but they still require that their primary science objectives be met by the end of the mission. The compromises made for these orbits consisted of the MWG reducing their requests on the downlink telemetry during C3 and E4 in order to accommodate the SWG's requests for telemetry during these scientifically important orbits, and SWG and AWG reducing their telemetry requirements for G2, which permitted MWG to utilize most of the capability for this orbit. As a result, the MWG developed the concept of two magnetospheric sub-tours, one at the beginning of the orbital tour and the second during the last orbits. The sub-tour concept is illustrated in Figure 3.

As a result of the science trades made to generate the resource allocation table, each of the working groups will address the most important of their key scientific questions about the Jovian system. For AWG, the focus of the science instruments will be an integrated study of small areas of Jupiter ("features") and those observations that are unique in terms of instrumental capability or geometric opportunity.

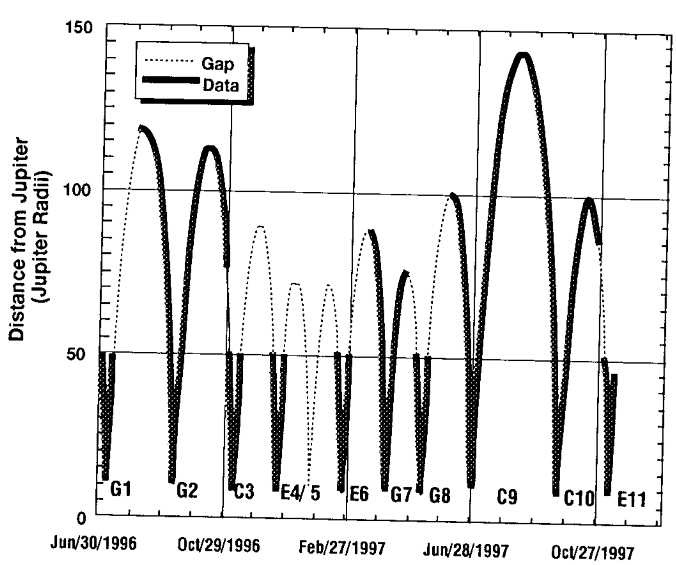

Figure 3. Magnetospheric Survey Subtours

The MWG's primary science objective is the magnetospheric survey. In order to investigate the large-scale topology and temporal behavior of the magnetosphere, the concept of two sub-tours was introduced. In addition to the above sub-tours, it is important that the region inside 50 R_j be continuously sampled for each orbit. A major objective in the second sub-tour is the journey into the unexplored regions of Jupiter's magnetotail. MWG's second primary objective has also been retained: high resolution coverage of the close flybys of the Galilean satellites.

The SWG satellite priorities are Io (single flyby), Europa, Ganymede, and Callisto. For the imaging experiment a high priority objective is to achieve global coverage complementary to that of Voyager as well as limited coverage 100-1000 times higher resolution than Voyager. For Near-Infrared Mapping Spectrometer (NIMS), the global coverage objective is to achieve coverage of a high percentage of the surface at modest spatial and spectral resolution, since all coverage of the satellites in the NIMS wavelength regime is new. The Photopolarimeter Radiometer observation set includes thermal and polarization observations. The ultraviolet experiment set includes limb scans as high priority. Most of the remaining observations for SWG consist of focused studies of very limited spatial extent for specific features or regions on the satellites.

5. MISSION PLANNING TOOLS

The flight software changes associated with operating the Galileo spacecraft using the LGA provide significant challenges and added complexity in the development of the science sequences. There are now complex interactions among collection and transmission of real-time science, transmission of engineering data, collection of recorded science, and playback of recorded data. For example, changes to the real-time science collection rate during the cruise portion of the orbit affect the amount of recorded science that can be played back during the same period. In a sample orbit planning exercise (SOPE) conducted in 1993 in order to understand the process of how science sequences are developed using the new Phase 2 flight software, it became clear that a mission planning tool would be needed to efficiently and successfully develop the flight sequences. The SOPE illustrated the need to modify an activity plan in development often and provide for fast turn-around estimates of the effects on spacecraft resources. In addition, in light of the current economic environment on Galileo, reductions in the mission operations workforce also require that automation tools be developed.

The key mission planning tool that is being developed as a result of these needs is called MIRAGE, for **M**ission **I**ntegration, **R**eal-time **A**nalysis, and **G**raphical Timeline **E**ditor. The MIRAGE software will expedite integration and conflict resolution, and provide modeling of spacecraft resources for science and engineering activities. It utilizes a graphical user interface with a timeline representation of the sequence in development. The MIRAGE software allows the user to quickly and easily manipulate science and engineering activities and provides for immediate feedback on the expected spacecraft resource usage resulting from these changes. The resources modeled within MIRAGE include onboard computer buffer usage, real-time science BTG, recorded science tape usage, play back BTG, tape recorder start/stop cycles, sequence memory usage, and resource claim violations with respect to the scan platform, the spacecraft attitude, and the real-time and record telemetry formats.

MIRAGE is the Galileo adaptation of the multimission PLAN-IT-2 (for **Plan I**ntegrated **T**imelines, version **2**) science planning software developed at JPL (see Reference 6). PLAN-IT-2 is an activity scheduling program that provides for sequence visualization to aid in the resolution of conflicts between spacecraft activities. It is written in LISP and runs on a UNIX workstation. PLAN-IT-2 presents the sequence to the user in the form of a timeline display showing the activities, conflicts, and any constraints that need to be considered in the sequence. The decision to use PLAN-IT-2 in the development of the MIRAGE software was driven by several factors, including the limited amount of software development time for MIRAGE, the immediate availability of a graphical user interface for timeline displays, and the capability to incorporate Galileo-specific constraint checking and spacecraft models. Adaptation of PLAN-IT-2 for Galileo involved reconfiguration of the display; incorporation of Galileo-specific resource constraint checks; definition of the format, content, and representation of the science and engineering activities; incorporation of resource modeling; and configuration of the internal time system and time representations. An example screen from the Galileo adaptation of PLAN-IT-2 is shown in Figure 4.

The primary use for MIRAGE is in the development of the OAPs. MIRAGE will compile the desired engineering, real-time science, and recorded science activities, model and track the resources listed above, and summarize resource usage by science instrument, science working group, or activity.

For the OAP integration activities, MIRAGE will be used in a sequence integration workroom environment. Here, all flight team members responsible for producing a conflict-free integrated plan will use MIRAGE's interactive and real-time capabilities to negotiate activity timings, move, delete, and/or update the activities, and display the effects of those changes in spacecraft resources. Workroom tools will include a large screen for display of MIRAGE outputs like Figure 4.

Two other tools being developed by Galileo to further increase the amount of automation involved in the sequence development process are SCAN-IT, which is a sequence review tool to provide automated checking of spacecraft and instrument flight rules, and OAPLINK, which is a tool used to expand high-level activities into sequence components. The SCAN-IT software is a Galileo adaptation of an existing multimission sequence review tool, which is a Unix based program and written in LISP. The adaptation process involves the incorporation of the relevant flight rules via a set of SCAN-IT scripts. The OAPLINK software has been in use on the Galileo flight team for the past couple of years.

6. IMPLICATIONS FOR FUTURE MISSIONS

While some of the work described here is peculiar to Galileo's anomaly response situation, a number of the mission planning factors discussed in this paper have far-reaching implications. First, data compression is likely to be an important element of future space missions and the mission planning implications of data compression described here, particularly the need to deal with the resulting uncertainty in effective downlink capability, will be widely applicable. Another conclusion is that software tools are now available to support activity planning and re-

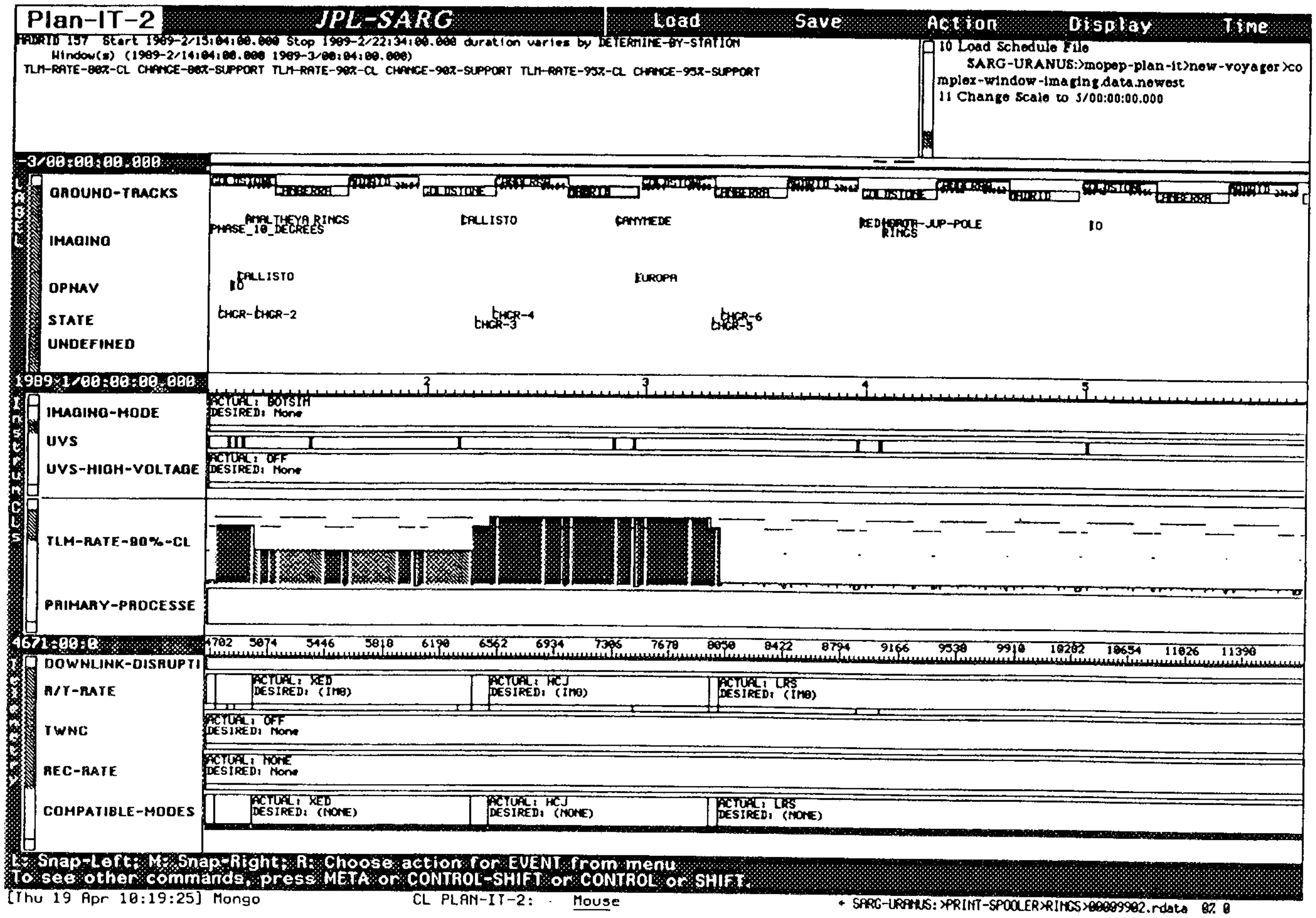

Figure 4. Sample Plan-It-2 Display

source allocation. These have great value and should be considered in the earliest stages of designing mission operations systems.

7. ACKNOWLEDGMENTS

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